

EvoCells – A Treemap Layout Algorithm for Evolving Tree Data

Willy Scheibel, Christopher Weyand, and Jürgen Döllner

Hasso Plattner Institute | Faculty of Digital Engineering, University of Potsdam
{willy.scheibel, juergen.doellner}@hpi.de, christopher.weyand@student.hpi.de

Keywords: Treemap Layout Algorithm, Time-varying Tree-structured Data, Treemap Layout Metrics

Abstract: We propose the rectangular treemap layout algorithm EvoCells that maps changes in tree-structured data onto an initial treemap layout. Changes in topology and node weights are mapped to insertion, removal, growth, and shrinkage of the layout rectangles. Thereby, rectangles displace their neighbors and stretch their enclosing rectangles with a run-time complexity of $O(n \log n)$. An evaluation using layout stability metrics on the open source ElasticSearch software system suggests EvoCells as a valid alternative for stable treemap layouting.

1 INTRODUCTION

Tree-structured data is subject to constant change. In order to manage change, understanding the evolution is important. An often used tool to communicate structure and characteristics of tree-structured data is the treemap (Shneiderman, 1992). Most layouts are based on a recursive partition of a given initial 2D rectangular area proportional to the summed weights of the nodes. Besides topology and associated weights, additional visual variables can be used (Carpendale, 2003), including extrusion of the 2D layout to 3D cuboids. The restricted use of the third dimension is reflected by the term 2.5D treemaps (Limberger et al., 2017b).

When used over time, treemap layouts are faced by their inherent instability regarding even minor changes to the nodes' weights used for the spatial layouting, impeding the creation and use of a mental map (Misue et al., 1995). Although a large number of treemap algorithms exist, most of them operate solely on the topology of tree-structured data and associated node weights at one point in time. This could lead to discontinuities between two successive layouts, contradicting the principle of visual data correspondence (Kindlmann and Scheidegger, 2014). Further, the use of an adapted initial area to represent change in the summed weight over time is underrepresented.

We propose a novel treemap layout algorithm that maps evolving tree data onto an initial treemap layout. This layout evolves alongside the tree data as all types of changes are mapped onto the layout (example in Fig. 1). Thereby, layout rectangles have a displacing behavior against their neighbors and a stretching be-

havior to their parents. We evaluate our approach with regard to algorithmic complexity and layout stability, together with a case-study in the domain of software analytics based on the software system ElasticSearch.

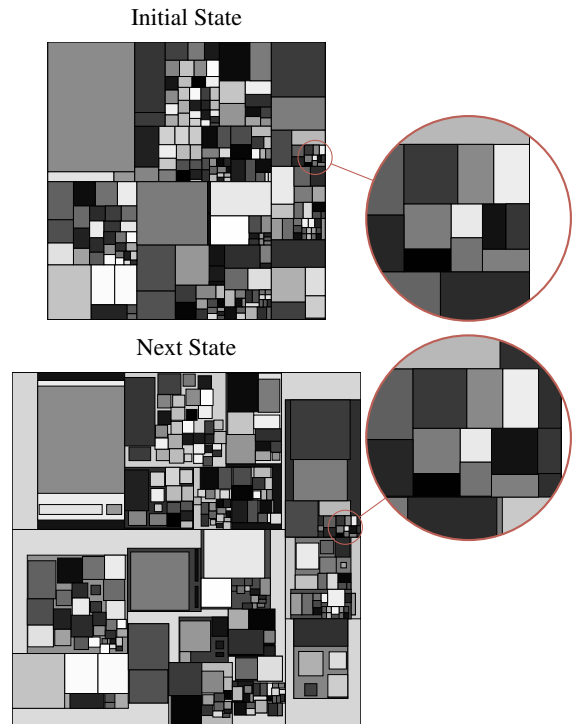


Figure 1: An initial treemap layout and the EvoCells-computed successor. The grayscale colors are pseudocolors encoding the id of the nodes. The dataset is an animal population hierarchy of the zoological garden in Munich using the population count as node weight (from 2011 to 2012).

2 RELATED WORK

The EvoCells algorithm is related to research on rectangular treemap layouting algorithms and general tree spatialization techniques with focus on evolution. The domain of software visualization includes additional layout techniques that takes the specifics in structure and evolution of tree-structured data into account.

Treemap layouting algorithms. Since the original treemap layout algorithm (Shneiderman, 1992), successive algorithms try to minimize characteristic metrics such as the average aspect ratio as an approximation to the readability of nodes (Bruls et al., 2000), distance change to approximate location stability of nodes between layouts (Bederson et al., 2002), and angular change to approximate neighborhood stability (Hahn et al., 2017). This resulted in algorithms using space-filling curves (Tak and Cockburn, 2013) and hybrid treemaps (Hahn and Döllner, 2017).

Tree layouting algorithms. Besides layouting algorithms resulting in rectangular treemaps, there are layouting algorithms that can be used for evolving tree-structured data as the resulting layouts have fewer degrees of freedom or are especially designed for evolution. Early examples are SunBurst View (Stasko et al., 2000) and the Hierarchical Bundle View (Holten, 2006). While taking only the topology of a tree into account, the Data-Jewelry Box algorithm is especially designed for evolving data (Yamaguchi and Itoh, 2003). More current approaches strive for more organic representation of nodes, such as Gosper Maps (Auber et al., 2013) where the space-filling Gosper curve is used to create map-like depictions of a tree and stable Voronoi treemaps by use of stable seed positions (Hahn et al., 2014).

Tree comparison techniques. Communicating the evolution of tree-structured data can be achieved by explicit comparison of two versions, e.g., by side-by-side comparison (Scheibel et al., 2016) and additional similarity indicators (Holten and Van Wijk, 2008; Telea and Auber, 2008). Another approach to encode the evolution of topology and node weights is to use a merged layout and encode the differences in-situ (Tu and Shen, 2007). Current expert systems use coordinated views on the same underlying data to communicate change (Guerra-Gómez et al., 2013).

Software visualization. In software visualization, treemaps and treemap-like approaches are used. There are software maps (Bohnet and Döllner, 2011),

Code Cities (Wettel and Lanza, 2008) and VERSO (Langelier et al., 2008) represent software systems using nested rectangles. However, depicting the evolution is addressed using differing approaches, too. The EvoStreets visualization technique (Steinbrückner and Lewerentz, 2010) represents the topology of a software system by streets and roads for the module hierarchy and cuboids and cylinders for source code files. To ensure visual node location stability over multiple states of a software system, dimensionality reduction can be used to compute the position for a node (Kuhn et al., 2008). Coordinated and multiple views are used, too (Reniers et al., 2014).

3 EVOCELLS LAYOUTING

Treemap algorithms up to date compute a layout by using one fixed state of a tree-structured dataset. We propose an algorithm that takes previously computed layouts into account, too. Although comparable to template-based treemaps (Kokash et al., 2014), our algorithm uses a packing instead of a splitting approach. EvoCells layouting computes a treemap layout for one state of a tree-structured dataset by applying the changes to a treemap layout of another state. Each change in topology and associated weights is mapped onto a change to the layout, performing an evolution of the initial layout (Fig. 2). The initial layout can be created using any rectangular treemap algorithm (e.g., Strip or Moore treemap layouting), including EvoCells-computed layouts themselves. The changes upon a node are mapped as follows:

Change leaf weight The corresponding rectangle is resized according to its weight.

Add leaf A new rectangle with area according to its weight is added within the parent rectangle.

Remove leaf The rectangle is removed and leaves empty space within the parent rectangle.

Move leaf The rectangle is removed from the layout and readded within the new parent.

Add parent A new treemap layout for the sub-tree of the new parent is computed and the resulting rectangles are added into the layout.

Remove parent The parent rectangle with all its children rectangles is removed from the layout.

Move parent The rectangle is removed (including child rectangles) from the layout and readded within the new parent, preserving the sublayout.

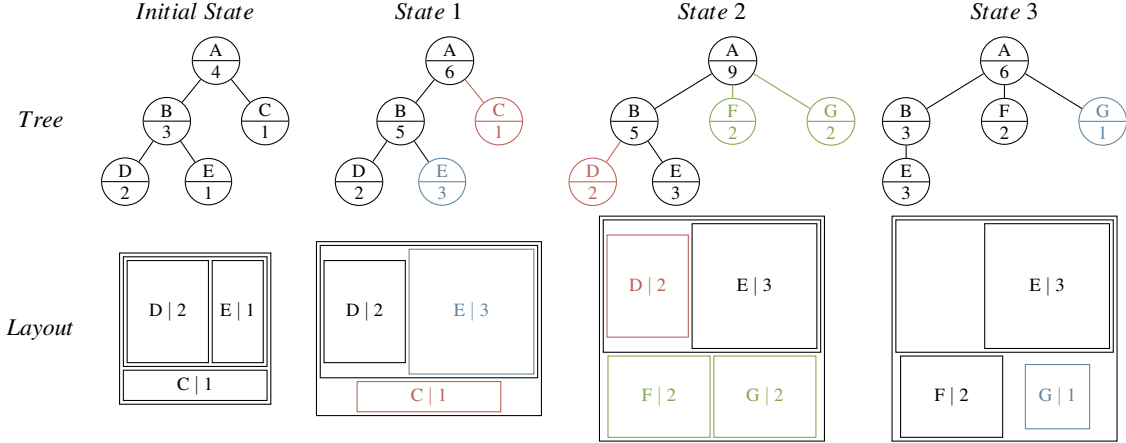


Figure 2: An exemplary evolution of a tree-structured dataset (top) and the reflection using EvoCells layouting (bottom). Each node and rectangle is labeled with a letter and a number representing identity and weight. Weight changes within one state are indicated by a blue color, added nodes by a green color and nodes that are removed in the next state are colored red.

Changes in topology are detected separately for parent nodes as a distinction allows for differing and optimized handling during the actual layout process. During growth of a rectangle, it has a displacing behavior against neighbors and a stretching behavior against the parent. Both displacement and stretching propagate through the layout and are resolved accordingly.

4 IMPLEMENTATION

An implementation of the EvoCells treemap layout algorithm depends on the definition of a dataset structure and the according change computation between two states. As treemap layout algorithm, EvoCells is designated to be used within treemap visualization systems (Fig. 3). We propose specialized interaction techniques for the exploration of a dataset over time.

4.1 Dataset Structure

EvoCells layouting operates on a set of *states* S . Each state S_i consists of a rooted tree G_i and a weight function w_i . A state describes the system state for one point in time. Since such a dataset represents one changing system, trees of contiguous states mostly include common structure. The intersection of all nodes over each tree includes at least the root v_{root} . A different root would imply a different system rather than an evolution. Each tree G_i satisfies the characteristics:

- $G_i = (V_i, E_i)$ is a rooted tree with $n = |V_i|$ nodes including the root v_{root} ,
- $m = n - 1 = |E_i|$ edges $E_i \subset V_i \times V_i$ directed from parent to child,

- only one node (v_{root}) with no parent:
 $\{v \in V_i \mid \nexists p \in V_i : (p, v) \in E_i\} = \{v_{root}\}$,
- every other node has exactly one parent:
 $\forall v \in V_i : (v \neq v_{root} \implies |\{p \in V_i \mid (p, v) \in E_i\}| = 1)$,
- and the weight $w(p)$ of a parent node p is the sum of its childrens' weights:
 $\exists (p, v') \in E_i \implies w_i(p) = \sum_{\{v \in V_i \mid (p, v) \in E_i\}} w_i(v)$.

The weights for each state are defined as $w_i : V_i \mapsto \mathbb{R}_0^+$, assigning a weight for each node in the state. The initial state is the state the initial layout is present for. An initial state other than S_0 is possible, too, and allows to compute layouts backwards in time.

4.2 Change Computation

Changes are computed by pairwise comparison of all nodes in two states of a tree-structured dataset. A domain-specific definition of node identity is required to match nodes between states. As the changes are applied to the initial layout in sequence, the order influences the resulting layout. We propose to order them by *removals*, *moves*, *weight changes*, and *additions*.

4.3 Change Application

Each change is sequently applied to the initial layout, resulting in area changes, insertion, or removals of rectangles. The area of a parent rectangle is only updated through propagation of leaf rectangle growth or displacement. A leaf rectangle area is defined by the associated node weight and is set in proportion to the sum of all leaf weights of the initial state *initWeightSum* (i.e., the weight of the root node) and

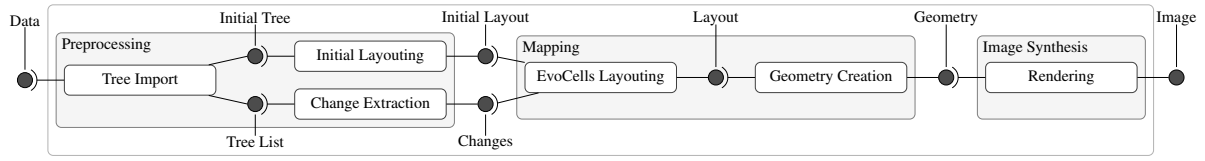


Figure 3: Example integration into a treemap visualization pipeline by means of an extension. EvoCells is integrated as two new stages (EvoCells Layouting and Change Extraction). The preexisting layout stage is reused to compute the initial layout.

their areas $initAreaSum$ (i.e., the root rectangle area for splitting layouts). The area function is defined by:

$$a_i(v) = w_i(v) \frac{initAreaSum}{initWeightSum}$$

In contrast to other treemap layout algorithms, the definition of a_i implies a constant area per weight over all states. This allows for directly comparable areas for all leaf nodes over all states.

Growing and shrinking nodes. A growth or shrinkage of the rectangle is applied in proportion to the increase or decrease in weight, respectively. While adjusting the rectangle to cover the target area, either its width, height, or both can be adapted. We propose a *squarifying* approach where the rectangle is gradually transformed to a square. The pivot point of the rectangle is its center. This approach modifies the visual characteristic (the aspect ratio) of the rectangle. Alternatively, both edge lengths can be resized proportionally to ensure aspect ratio stability.

Appearing nodes. When inserting a new node rectangle into the layout within a parent, the actual width and height of the rectangle needs to get computed as well as the insertion position. As the area of the rectangle is computed from one single weight value, we propose a square. There are several approaches to place the new rectangle in the layout. We suggest a placement strategy that analyzes the four sides of the parent rectangle on which the new rectangle can be inserted to minimize the parent rectangle stretching and whitespace. This provides a reasonable trade-off between layout stability and computational effort.

Disappearing nodes. A removed node allows for two opponent approaches. The first approach retains the corresponding rectangle but mark it as a *ghost* (e.g., allowing for specialized depiction in a treemap visualization, cf. Fig. 4). These ghosts can be deferred removed after several more state changes. The second approach is the immediate removal from the layout. We recommend the ghost approach to enhance subsequent visual depiction and maintaining a mental map.

4.4 Interaction Techniques

The main scenario for EvoCells layouts is improved layout stability for treemap-based exploration of a tree-structured dataset over time. To support this, the user has to select an initial state. From this state, the dataset can be explored step by step (forwards or backwards in time). To reduce free space, the user can restore a compact treemap layout of the current state.

Choose initial state. This interaction is similar to stepping through states in a treemap visualization system. Effectively, the user chooses a state using the existing interaction techniques and starts an evolution exploration mode, where the current state is used as the initial one for EvoCells layouting.

Step state forward. One scenario is the exploration of future changes from an initial state. Using this, the user may step states forward. The occurring changes are applied to the layout in chronological order.

Step state backward. Contrary to stepping forward in time, the user may choose to explore the preceding changes. The changes are applied in reverse chronological order and in reverse effect (e.g., an actual change may have been an appearing node but through the backward exploration in time, this change is applied as a disappearing node).

Contract treemap layout. When finalizing an exploration, the user may return to a treemap layout that is created using the layouting algorithm of the initial layout but with the current target state.

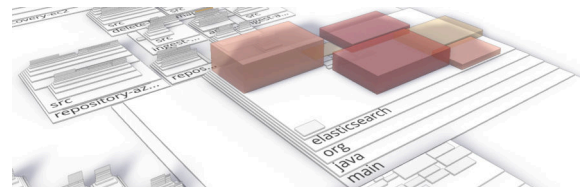


Figure 4: Removed nodes from the dataset are rendered as transparent *ghosts* to preserve the mental map (screenshot taken from a software map visualization).

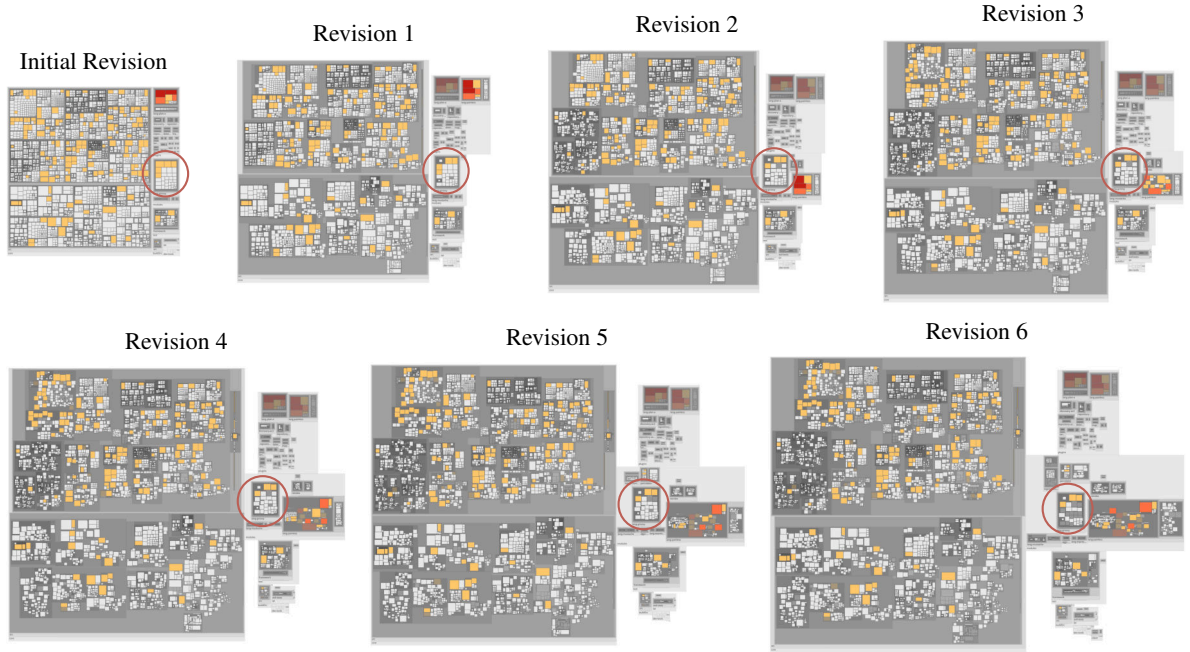


Figure 5: The evolution of the ElasticSearch software project over six months using EvoCells layouting. Removed nodes remains as *ghosts* in the layout. A particularly stable module is circled red in each revision.

5 EVALUATION AND RESULTS

We evaluate the algorithmic complexity of EvoCells and stability of computed treemap layouts. Further, we provide a short case study on the software project ElasticSearch as a software visualization use case.

Software systems are a domain of tree-structured data. The systems are contiguously measured by means of software metrics, resulting in dataset containing states for different points in time. Typically, software projects are developed by applying individual changes to source code files. To differentiate between removed, added, removed, and changed files, tracking the identity is important (Prause, 2009). Each change to a source code file may change a measured metric value. Those changes are collected and grouped to commits that reflect semantically coherent changes to a software system—the revisions. Multiple commits can be aggregated to represent higher-level changes to the software system (Fig. 6).

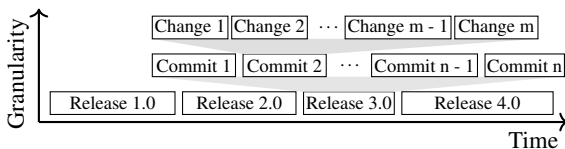


Figure 6: Different levels of granularity to track changes of a software system. EvoCells layouting can be used on each granularity level with differing results for the layout.

5.1 Algorithmic Complexity Evaluation

The algorithmic complexity of the implementation is $O(ab^2 \log_b n)$ with n being the number of nodes in the hierarchy, a the number of changes compared to the initial state, and b the average number of children for an inner node. Since any such algorithm must consider all changes and each change potentially effects a node and all of its parents, our implementation reaches the trivial lower bound in a and n . The resolution of overlapping rectangles by means of displacement (currently in $O(b^2)$) can further be optimized to a lower bound of $O(b \log b)$ (Dwyer et al., 2007).

Considering typical datasets, the average number of children for an inner node is considerably smaller than the overall number of nodes. Assuming b as constant and approximating the number of changes a per state change by the number of nodes n (i.e., in a node cannot be changed more than once in a state). Therefore, the complexity can be simplified to $O(n \log n)$.

5.2 EvoCells for Software Visualization

For the case study, screenshots, and layout metric computation, we implemented the EvoCells layout algorithm into a prototypical software map visualization system. The visualization pipeline is extended by a change extraction and the EvoCells layouting algorithm (see Fig. 3). In our example application us-

ing a software map visualization of ElasticSearch, the file hierarchy and one software metric of the dataset is used for the tree topology and associated weight attribute. Here, the weight metric represents the quantity of source code in the software system by using the real lines of code (RLoC) as weight attribute. The initial layout was generated with the Squarified treemap layout (Bruls et al., 2000) algorithm. We chose the additional visual variable color that is mapped from the cyclomatic complexity. The evolution of the layout shows differences for modules with high changes in topology and weights. Unchanged and marginally changed modules have a high layout stability (Fig 5).

5.3 Layout Stability

The EvoCells layouting algorithm is compared against the algorithms Hilbert, Moore, Slice’n’Dice, Spiral, Squarified, Strip, and inverting Strip treemap layouting. The layout stability is measured on the ElasticSearch software project dataset using all seven revisions. On average, the weight of more than one thousand nodes changes with each revision. We analyzed the previously published metrics *Average Aspect Ratio*, *Location Drift*, and *Relative Direction Change* (Hahn et al., 2017) as well as the two additional metrics, *Average Aspect Ratio Change* and *Relative Parent Change*. The metrics for the seven revisions were computed separate, pairwise, or—in case of location drift—in sum. The separate and pairwise metrics were aggregated to build a score over all revisions (see Fig. 7). To construct a single score per layout algorithm, we combined the results using the *Borda Count* (Hornik and Meyer, 2007).

Due to the packing approach, a layout generated by EvoCells layouting is most probably not restrained to a unit square. Thus, we applied the metric computation to a normalized version of the layout. Depending on the type of normalization, each metric can be affected. We chose an aspect-ratio-preserving normalization to an area equal to the area of the unit square. This does not affect the average aspect ratio, its change, the relative parent change, and relative direction change metrics. Values of the location drift are more comparable regarding the other algorithms.

Average Aspect Ratio. The algorithms Spiral, Squarified and EvoCells perform best in terms of average aspect ratio with values between 35 and 37. The aspect ratio of the Slice’n’Dice algorithm with 864 is the highest among all compared algorithms. The above-average results of EvoCells originate from the underlying Squarified algorithm for the initial layout.

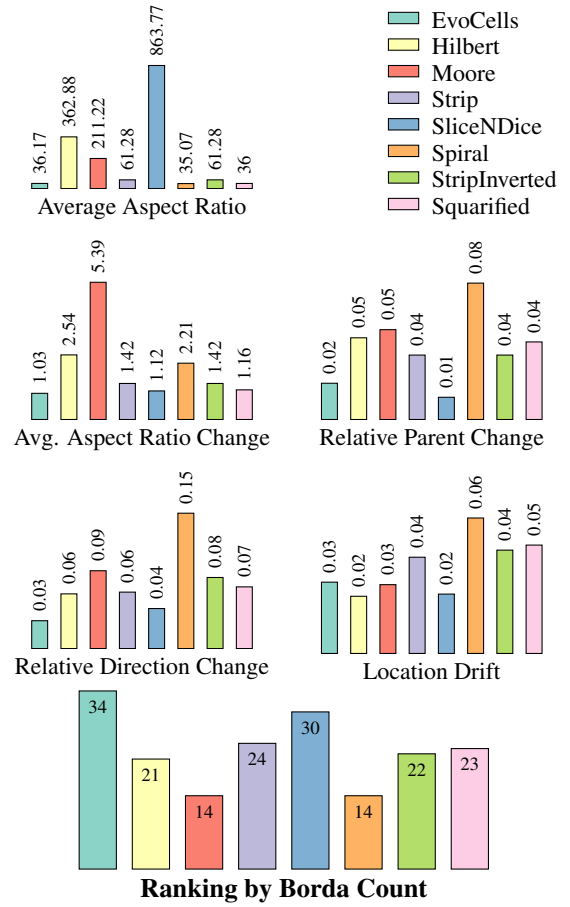


Figure 7: Comparison of the layout metrics *average aspect ratio*, *average aspect ratio change*, *relative parent change*, *relative direction change*, and *location drift* (Bederson et al., 2002; Hahn et al., 2017). A compound score using Borda Count ranks the layout algorithms.

Average Aspect Ratio Change. This layout metric measures the changes in percentage of aspect ratios between two states and thus, approximates visual resemblance. EvoCells has the most stable aspect ratios, which change on average by 3% between two subsequent revisions. In contrast to the high average aspect ratio of Slice’n’Dice, its 12% change is the second lowest among the compared algorithms. This metric ignores changes in orientation, which benefits Slice’n’Dice and penalizes algorithms as Moore.

Relative Parent Change. The relative parent change measures the average change of position in percent relative to the center of the parent rectangle. This approximates the chance a user can relocate the rectangle once they relocate the parent rectangle. Slice’n’Dice has the best result with 0.01 closely followed by EvoCells (0.02). With a relative parent change of 0.08, the Spiral algorithm is most unstable.

Relative Direction Change. The lowest relative direction is measured for EvoCells with 0.03. The highest value is 0.15 for Spiral, which is approximately 66% more than Moore—the next lower algorithm.

Location Drift. Moore and Slice’n’Dice have the lowest location drift (0.02). The highest location drift is 0.06 by Spiral. The result of 0.03 for EvoCells depends on the normalization we chose to apply. On the one hand the normalization prevents location changes beyond a rectangle with the area of a unit square, on the other hand, it distorts the position of stationary nodes, when the layout bounds change. This approach favors centrifugal rectangle movements.

Ranking by Borda Count The compound score shows EvoCells is a treemap layout algorithm with competitive stability characteristics for the ElasticSearch dataset. It leads the score with special suitability in the average aspect ratio change, relative parent change, and relative direction change. Although this result has to be verified using more datasets and greater time spans to get reliable it indicates that EvoCells is suitable for stable treemap layouting.

5.4 Supplementary Features

A treemap visualization system may be extended by EvoCells layouting to support more stable treemap layouts during evolution exploration. However, further interaction and visualization techniques are required to provide a sophisticated tool. For example, adding space between a parent rectangle and its children helps in depicting the hierarchical structure (Lü and Fogarty, 2008). Besides layout-independent color and height (Dübel et al., 2014) for leaf nodes, an additional visual variable such as texture (Holten et al., 2005) and sketchiness for uncertainty (Limberger et al., 2016) can be used. The EvoCells layouting algorithm is constructed to compute successive layouts where each two of them are interpolatable without any node’s rectangle overlapping a sibling or protruding its parent rectangle. This allows for disentangled animated transitions (Bladh et al., 2005). Further, some software projects have many modules and source code files, making them hard to visualize without visual clutter and meaningful pixels-to-elements ratio. This can be avoided using importance-based aggregation (Limberger et al., 2017a). In addition to the reduction of visual elements, the aggregation can be used to limit the tree depth on which EvoCells layouting operates, improving computation run-time.

6 CONCLUSIONS

The EvoCells layouting algorithm is a novel rectangular treemap layouting algorithm that applies the evolution in topology and associated weights of a tree-structured dataset onto an initial layout. This layout algorithm performs well with regard to layout stability and readability metrics. A compound Borda Count score computed using the evolution of one open source software project highlights EvoCells layouting as the best algorithm. It is especially useful for map themes using a weight mapping and data domains with often-changing topology and nodes’ weights (e.g., software system data and business intelligence data, cf. Fig. 1). The algorithm can be integrated into existing treemap-based visualization systems as an extension to the layouting phase.

For future work, we plan to integrate a layout postprocessing where each node is attracted by the center of the parent rectangle while remaining non-overlapping. Parents may shrink during this process, providing a gradually shrinking layout and thereby, reduce empty space and overall layout size. Besides the encoding of evolution in the layout rectangles of a software map, the depiction of evolution in other visual variables for leaf nodes can be expressed by means of trends (Würfel et al., 2015) and Data Vases (Thakur and Rhyne, 2009). A treemap layout template (Kokash et al., 2014) may be derived from an EvoCells layout to allow for an animated transition back to a space-filling layout.

ACKNOWLEDGEMENTS

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the paper. This work was funded by the German Federal Ministry of Education and Research (BMBF) within the BIMAP project (www.bimap-project.de). We want to thank Seerene (www.seerene.com) for providing the ElasticSearch project and Munich zoological garden datasets.

REFERENCES

- Auber, D., Huet, C., Lambert, A., Renoust, B., Sallaberry, A., and Saulnier, A. (2013). Gospermap: Using a gosper curve for laying out hierarchical data. *IEEE TVCG*, 19(11):1820–1832.
- Bederson, B. B., Shneiderman, B., and Wattenberg, M. (2002). Ordered and quantum treemaps: Making effective use of 2d space to display hierarchies. *ACM Transactions on Graphics*, 21(4):833–854.

- Bladh, T., Carr, D. A., and Kljun, M. (2005). The effect of animated transitions on user navigation in 3d treemaps. In *Proc. IEEE IV*, pages 297–305.
- Bohnet, J. and Döllner, J. (2011). Monitoring code quality and development activity by software maps. In *Proc. ACM MTD '11*, pages 9–16.
- Bruls, M., Huizing, K., and van Wijk, J. J. (2000). Squarified treemaps. In *Proc. Joint EUROGRAPHICS/IEEE TCVG Data Visualization '00*, pages 33–42.
- Carpendale, M. (2003). Considering visual variables as a basis for information visualisation. Technical report, University of Calgary.
- Dübel, S., Röhlig, M., Schumann, H., and Trapp, M. (2014). 2d and 3d presentation of spatial data: A systematic review. In *Proc. IEEE 3DVis '14*, pages 11–18.
- Dwyer, T., Marriott, K., and Stuckey, P. J. (2007). Fast node overlap removal—correction. In *Proc. Springer Graph Drawing '06*, pages 446–447.
- Guerra-Gómez, J., Pack, M. L., Plaisant, C., and Shneiderman, B. (2013). Visualizing change over time using dynamic hierarchies: Treeversity2 and the stemview. *IEEE TVCG*, 19(12):2566–2575.
- Hahn, S., Bethge, J., and Döllner, J. (2017). Relative direction change – a topology-based metric for layout stability in treemaps. In *Proc. SciTePress IVAPP '17*, pages 88–95.
- Hahn, S. and Döllner, J. (2017). Hybrid-treemap layouting. In *Proc. EuroVis '17 – Short Papers*.
- Hahn, S., Trümper, J., Moritz, D., and Döllner, J. (2014). Visualization of varying hierarchies by stable layout of voronoi treemaps. In *Proc. SciTePress IVAPP '14*, pages 50–58.
- Holten, D. (2006). Hierarchical edge bundles: Visualization of adjacency relations in hierarchical data. *IEEE TVCG*, 12(5):741–748.
- Holten, D. and Van Wijk, J. J. (2008). Visual comparison of hierarchically organized data. *EG Computer Graphics Forum*, 27(3):759–766.
- Holten, D., Vliegen, R., and van Wijk, J. J. (2005). Visual realism for the visualization of software metrics. In *Proc. IEEE VISSOFT '05*, pages 1–6.
- Hornik, K. and Meyer, D. (2007). Deriving consensus rankings from benchmarking experiments. In *Springer Advances in Data Analysis*, pages 163–170.
- Kindlmann, G. and Scheidegger, C. (2014). An algebraic process for visualization design. *IEEE TVCG*, 20(12):2181–2190.
- Kokash, N., de Bono, B., and Kok, J. (2014). Template-based treemaps to preserve spatial constraints. In *Proc. SciTePress IVAPP '14*, pages 39–49.
- Kuhn, A., Loretan, P., and Nierstras, O. (2008). Consistent layout for thematic software maps. In *Proc. IEEE WCRE '08*, pages 209–218.
- Langelier, G., Sahraoui, H., and Poulin, P. (2008). Exploring the evolution of software quality with animated visualization. In *Proc. IEEE VL/HCC '08*, pages 13–20.
- Limberger, D., Fiedler, C., Hahn, S., Trapp, M., and Döllner, J. (2016). Evaluation of sketchiness as a visual variable for 2.5d treemaps. In *Proc. IEEE IV '16*, pages 183–189.
- Limberger, D., Scheibel, W., Hahn, S., and Döllner, J. (2017a). Reducing visual complexity in software maps using importance-based aggregation of nodes. In *Proc. SciTePress IVAPP '17*, pages 176–185.
- Limberger, D., Scheibel, W., Trapp, M., and Döllner, J. (2017b). Mixed-projection treemaps: A novel approach mixing 2d and 2.5d treemaps. *Proc. IEEE IV '17*.
- Lü, H. and Fogarty, J. (2008). Cascaded treemaps: Examining the visibility and stability of structure in treemaps. In *Proc. GI '08*, pages 259–266. Canadian Information Processing Society.
- Misue, K., Eades, P., Lai, W., and Sugiyama, K. (1995). Layout adjustment and the mental map. *Elsevier Visual Languages & Computing*, 6(2):183–210.
- Prause, C. R. (2009). Maintaining fine-grained code metadata regardless of moving, copying and merging. In *Proc. IEEE SCAM '09*, pages 109–118.
- Reniers, D., Voinea, L., Ersoy, O., and Telea, A. (2014). The solid* toolset for software visual analytics of program structure and metrics comprehension: From research prototype to product. *Elsevier Science of Computer Programming*, 79:224–240.
- Scheibel, W., Trapp, M., and Döllner, J. (2016). Interactive revision exploration using small multiples of software maps. In *Proc. SciTePress IVAPP '16*, pages 131–138.
- Shneiderman, B. (1992). Tree visualization with tree-maps: 2-d space-filling approach. *ACM Transactions on Graphics*, 11(1):92–99.
- Stasko, J., Catrambone, R., Guzdial, M., and McDonald, K. (2000). An evaluation of space-filling information visualizations for depicting hierarchical structures. *Elsevier Human-Computer Studies*, 53(5):663–694.
- Steinbrückner, F. and Lewerentz, C. (2010). Representing development history in software cities. In *Proc. ACM SOFTVIS '10*, pages 193–202.
- Tak, S. and Cockburn, A. (2013). Enhanced spatial stability with hilbert and moore treemaps. *IEEE TVCG*, 19(1):141–148.
- Telea, A. and Auber, D. (2008). Code flows: Visualizing structural evolution of source code. *EG Computer Graphics Forum*, 27(3):831–838.
- Thakur, S. and Rhyne, T.-M. (2009). Data vases: 2d and 3d plots for visualizing multiple time series. In *Springer Advances ISVC*, pages 929–938.
- Tu, Y. and Shen, H. W. (2007). Visualizing changes of hierarchical data using treemaps. *IEEE TVCG*, 13(6):1286–1293.
- Wettel, R. and Lanza, M. (2008). Visual exploration of large-scale system evolution. In *Proc. IEEE WCRE '08*, pages 219–228.
- Würfel, H., Trapp, M., Limberger, D., and Döllner, J. (2015). Natural Phenomena as Metaphors for Visualization of Trend Data in Interactive Software Maps. In *Proc. EG CGVC '15*.
- Yamaguchi, Y. and Itoh, T. (2003). Visualization of distributed processes using “data jewelry box” algorithm. In *Proc. IEEE CGI '03*, pages 162–169.